

Special Issue: Semiconductor devices that lead the way to a new lifestyle and a paradigm shift



**HIGH FREQUENCY SEMICONDUCTOR DEVICES FOR DIGITAL  
MOBILE TELCOMMUNICATIONS IN THE 1.8 TO 2.0 GHz  
BANDWIDTH**

By Chushiro Kusano\*, Isao Yoshida\*, Kazuo Sato\*\*, Kazuhiko Kawai\*\*

\* Hitachi Ltd. SICD, Doctor of engineering

\*\* Hitachi Ltd. SICD

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The rate at which the use of mobile communication systems such as automobile telephones and cellular telephones is spreading is spectacular; the number of users is expected to continue to increase rapidly. To meet the demands of this situation systems are rapidly being switched from analog to digital, and high frequencies in the 1.8 to 2.0 GHz bandwidth, greatly exceeding the formerly used frequencies in the 800 MHz bandwidth, are coming into use.

Meanwhile, it has become necessary for semiconductor components to have improved performance, reduced size and a high degree of integration to provide portable terminals that are small and light in weight, permit conversations to continue for a long time, and can be placed on standby to receive incoming calls. In particular, the high frequency devices that constitute the wireless portion of the terminal, which send and receive electromagnetic waves, are required to have higher and higher performance as the frequency bandwidth becomes higher.

To meet these needs Hitachi Ltd., aiming at application to mobile digital communication systems in the 1.8 to 2.0 GHz bandwidth, has developed a miniature package high frequency power amplifier module using an Si-MOSFET (field effect transistor) of new construction; an ultraminiature package GaAs-MMIC (microwave monolithic IC) incorporating a fully matched circuit; and a low power consumption Bi-CMOS

frequency synthesizer IC.

## 1. Introduction

The rate at which the use of mobile communication systems, which permit communication with anybody, at any time and in any place, is spreading is spectacular. As of August 1996, the numbers of automobile telephone and cellular telephone subscribers were more than 90,000,000 people worldwide and more than 17,000,000 people in Japan. These numbers are expected to increase at about 20% per year. At present, analog systems and digital systems are coexisting, but it is expected that to accommodate the increasing number of subscribers there will be rapid switching to digital systems, and higher frequencies will be used.

The move to higher frequency specifically involves moving from the previous 800 to 900MHz bandwidth to the 1.8 to 2.0 GHz bandwidth. New services which have been started include the PHS (Personal Handyphone System) in Japan; the PCN (Personal Communication Network) and DECT (Digital European Cordless Telecommunications) in Europe; and the PCS (Personal Communication Services) in the United States. In particular, the 1.8 to 2.2 GHz bandwidth has already been assigned as a worldwide high frequency bandwidth for the FPLMTS (Future Public Land Mobile Telecommunication System); it is expected that the use of this frequency bandwidth will increase (see Fig. 1).

Meanwhile, in order for the use of mobile communications to spread, it is essential to have low priced portable terminals that are small and light in weight, can be used for conversations lasting a long time, and are capable of being placed on standby to receive incoming calls. To meet this demand, it is essential for electronic components, particularly semiconductor components, to have improved performance, lower power consumption, and to be smaller in size and more highly integrated. Active research and development efforts to accomplish these goals are under

way. In particular, regarding high frequency devices which make up the wireless sections that send and receive electromagnetic waves, are required to have higher performance as the frequency bandwidth becomes higher. To meet this demand, Hitachi Ltd. has been developing a variety of semiconductor devices for use in mobile communications.

Here we discuss newly developed high frequency device for use in mobile communications in the 1.8 to 2.0 GHz bandwidth, including an Si-MOSFET high frequency power amplifier module, a GaAs-MMIC and a Bi-CMOS frequency synthesizer IC.

## **2. Mobile Communication Systems and High Frequency Devices**

A basic block diagram and the device technology of a cellular telephone are shown in Fig. 2. Functionally, it consists of a wireless section that sends and receives electromagnetic waves, and a base band section that processes audio signals and controls input and output. The wireless section consists of a high frequency section and an intermediate frequency section. The high frequency section consists of an antenna switch which in turn is divided into a receiving side and a sending side for electromagnetic waves (1.8 to 2 GHz), a low noise amplifier, a sending and receiving mixer and a power amplifier. The intermediate frequency section consists of an intermediate frequency amplifier, an AC modulator and a frequency synthesizer.

Cellular telephones are required to be small and light in weight, and to be capable of sustaining long conversations and of being put on standby to receive calls. For this reason, semiconductor devices used in cellular telephones are required to be highly integrated and to run on low voltage, with low power consumption. In particular, in the wireless section, much higher performance is required in the 1.8 to 2.0 GHz bandwidth than in the 800 to 900MHz bandwidth.

Specific semiconductor device technologies that are

used in the wireless section include an Si-MOSFET that is capable of high frequency operation; low noise, low distortion, low loss GaAs devices; and Bi-CMOS technology that makes it possible to have high frequency operation and a high degree of integration at the same time.

### **3. The Si-MOSFET High Frequency Module**

Hitachi Ltd. has been continuing research and development work on silicon power MOSFETs for about 25 years (see Fig. 3). At first, the Si-MOSFET was developed for audio use, but by changing the gate material from multicrystalline silicon to metallic molybdenum (Mo) high frequency performance was dramatically improved. In addition, by using fine geometry processing technology it became possible for an Si-MOSFET with molybdenum gate structure to operate at frequencies of 1 GHz and higher, and we succeeded in developing a highly efficient power MOSFET (L Series) that can be used in cellular telephones used in mobile communication systems 1).

The Si-MOSFET power amplifier (high frequency module) has high power gain, capable of operating as a single power supply with superior stability to load fluctuations, characterized by the simplicity of the circuit configuration of a set 2). Recently it has become widely used in cellular telephones used in the European digital cellular GSM (Global System for Mobile Communications). In this section, we discuss two technologies that are coming to be used in the high frequency bandwidth, the MOSFET (L4) of new structure developed for use in the 1.8 to 1.9 GHz bandwidth, and miniature package technology.3)

Until now, for the molybdenum gate electrodes used in L Series MOSFETs 0.7  $\mu\text{m}$  was the limit of mass production technology. To make improved performance possible in the future, we have changed the gate electrode structure in L4 devices. The cross-sectional structures of L4 devices and previous devices are shown in Fig. 4. A feature of L4 devices is the aluminum/silicide 2-layer gate structure,

with a silicide gate electrode that has been reduced in size to 0.5  $\mu\text{m}$  and on top of it a low resistance aluminum electrode. This structure has permitted the gate length to be made finer at the same time that the gate resistance is decreased, so that the device can be realized at a frequency of 1.9 GHz, with a power supply voltage of 4.8 V, gate width of 7.5 mm and 1 W output, giving a power addition efficiency of 55%. Compared to the previous device (the L3 with 0.8  $\mu\text{m}$  gate length) the output has been increased by 30% and the power addition efficiency has been improved by 9%. In addition, a high frequency module for use in the 1.9 GHz bandwidth PCS has been prototyped; it provides good high frequency response, with a power supply voltage of 4.8V, output power of 2W and overall efficiency of 45%.

Development of miniaturized packages for use in high frequency modules is an important requirement to make cellular telephones smaller. Hitachi Ltd. has developed packages that are greatly decreased in size that are capable of withstanding existing surface mounting and reflow soldering technologies (see Fig. 5). In addition, we have recently developed our Model K package with a new leadless type structure employing a multilayer ceramic substrate. The K package has a volume of about 0.2 cc, which requires half or less the surface area for mounting as previous packages, with about 1/3 the volume.

We now are aiming for further improvements in high frequency response, operation at lower voltage and improved functionality.

#### **4. GaAs-MMIC**

In the wireless section of a cellular telephone that processes high frequency signals of frequency 800 MHz and higher, input/output impedance matching is essential to suppress power loss. Since the crystalline substrate used in a GaAs device is semi-insulating, it is possible to form a low loss matching circuit on the GaAs chip. For this reason, the number of externally mounted components is greatly

decreased, making assembly and adjustment much easier than with Si-LSI.

Aiming at commercial production of GaAs-MMIC devices that have these characteristics, Hitachi Ltd. has developed device and process technologies for, for example, low noise, low loss GaAs-FETs and spiral inductors with thick film gold plating, and has put GaAs-MMIC chip sets for use in the 1.9 GHz bandwidth into mass production 4) 5). This time, to meet market demands for still further size reduction, we have developed overall high frequency circuit design technology in which the package constant is incorporated as part of the circuit. We have succeeded in incorporating an internal 50 ohm matching input/output circuit while at the same time decreasing the chip size, making it possible to mount the chip on a miniature plastic package (MPAK5 or 6).

The MMIC (HA22012) low noise amplifier chip that has been developed is shown in the photograph on page 21. Compared to MMICs using previous technology, the surface area has been decreased by about 60%. As a result, as shown in Fig. 6 it has become possible to use the MPAK5 miniature package, with the mounted area decreased by about 1/4 from our own predecessor model (the TSSOP14).

The high frequency characteristics of the HA22012 are shown in Fig. 7. To achieve low noise, a dual gate FET structure with 0.4  $\mu\text{m}$  gate length and small parasitic capacitance is used. The characteristics are good: power gain 13.5dB, noise index 1.9dB and output intercept point (IP3) 12.5dBm in operation at 1.9 GHz with power supply voltage 3V and operating current 3mA.

The characteristics of the HA22016 antenna switch, developed with the aim of package miniaturization (MPAK6), are shown in Fig. 8. An SPDT (Single Pole Double Throw) antenna switch is used to switch between input and output while sending and receiving. The following characteristics are required:

- (1) The loss when a signal passes through the system must be low.
- (2) The distortion during large signal action must be small.

(3) The isolation characteristics between terminals when the unit is OFF must be good (there must be high isolation). For this reason, we have developed an FET with small ON resistance and threshold voltage of -2V and a dual gate FET that has low distortion characteristics. In addition, we have newly developed a type of circuit in which the parasitic capacitance of the FET is canceled out by a spiral inductor 6). In the past the load voltage was controlled between 0V and -3V, but by connecting capacitors to the signal terminal and the ground terminal we have succeeded in establishing positive voltage control (between +3V and 0V).

We intend to continue our efforts at package miniaturization and compound functionality in order to meet the needs for GaAs-MMICs.

## **5. Bi-CMOS High Frequency Analog LSI**

Semiconductor devices for use in the intermediate frequency section are required to have both analog and digital functionality, and a high degree of integration. Hitachi Ltd. has developed and put into commercial production a PLL (Phase-Locked Loop) frequency synthesizer, for use in cellular telephones, as a high frequency analog LSI achieved through a Bi-CMOS process [ $f_T$  (cutoff frequency) = 15 GHz] having both bipolar transistor high frequency characteristics and the high degree of integration of a CMOS (see Table 1) 7).

This time, in order to conform to the conversion of mobile communication systems from analog to digital and to permit use in the high frequency bandwidth, we have developed the HD155007T and the HD155008T as dual PLL frequency synthesizers. The operating frequencies of the HD155007T are 510MHz and 2 GHz; those of the HD155008T are 510MHz and 1.1 GHz. The principal characteristics of the HD155007T are shown in Table 2. Aiming at application in digital mobile communications, we have pursued our development work keeping in mind the need for low power consumption, high speed lockup during frequency conversion.

and low noise. We have achieved low operating voltage (from 2.7V), an integrated power saving mode and integration of a fixed current type charge pump circuit.

A high precision fixed current drive circuit is used in the charge pump circuit. The circuit configuration is one in which the phase noise characteristics and lockup characteristics do not fluctuate with fluctuation in environmental conditions such as power supply voltage and ambient temperature. The HD155007T output spectrum is shown in Fig. 9. We achieved good characteristics with phase noise of  $-78.6\text{dBc/Hz}$  (1KHz offset) and spurious level of  $-77\text{dBc}$  at 600KHz offset, with a center frequency of 646.7MHz and phase comparison frequency of 300KHz. The charge pump current level when the frequency is switched can be set to either Hi or Lo mode. By switching to Lo mode after lockup is done at high speed in Hi mode, we have achieved both high speed lockup and low noise characteristics at the same time. In addition, the lockup time is set to be short after power saving mode is released, so the charge pump circuit output in power saving mode is saved as a charge in the loop filter capacitor as the high impedance state. We have also achieved low power consumption: the current consumption in power saving mode is held to not more than 400 to 500 nA and not more than 1 $\mu\text{A}$ .

We intend to continue our pursuit of high performance, high functionality and lower power consumption, and to continue developing compound function, high frequency analog LSIs with highly integrated high frequency analog function blocks, with PLL frequency synthesizers at the core.

## 6. Summary

Here we have reported on several key devices for rapidly expanding mobile communication systems: the Si-MOSFET high frequency module, the GaAs-MMIC and the Bi-CMOS frequency synthesizer IC.

The spread of mobile communication systems has been spectacular. Wireless communication functions have now

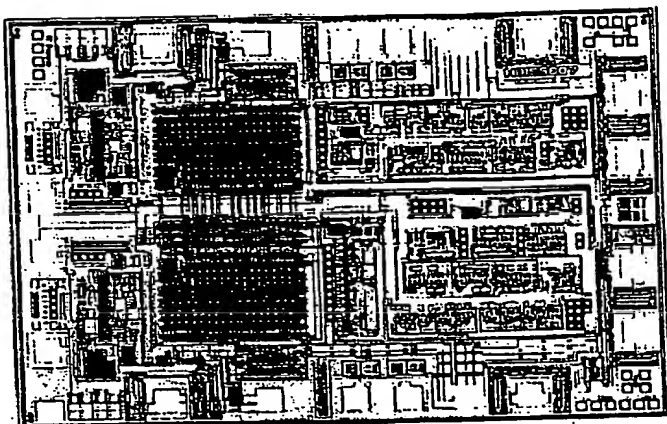


become indispensable not only in cellular telephones but also in personal computers and PDAs (Personal Digital Assistants). For this reason, the high frequency devices discussed here require still higher performance, higher degree of integration and higher functionality. To meet this demand, we intend to continue active efforts to develop high frequency devices for use in mobile communications and put them into commercial production.

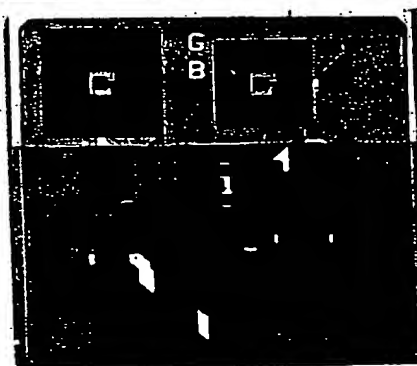
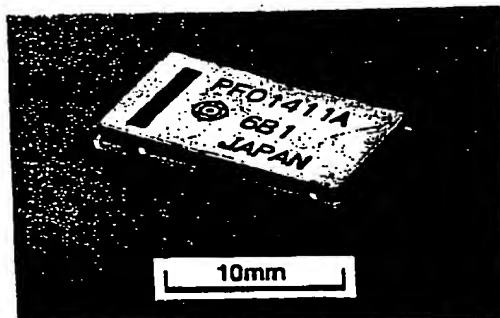
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Si-MOSFET  
High Frequency  
Power Amplifier Module



Bi-CMOS Frequency Synthesizer IC



GaAs-MMIC (Low noise amplifier)

**Abbreviation:**

MOSFET(Metal-Oxide-Semiconductor Field-Effect Transistor)

Bi-CMOS(Bi-Complementary Mos)

MMIC(Microwave Monolithic IC)

**High Frequency Power Amplifier Module, GaAs-MMIC and High Frequency Synthesizer IC for Use in Mobile Telephones**

We have developed a high frequency power amplifier module in a miniature package that is an SI-MOSFET of new construction and has improved power efficiency; a GaAs-MMIC incorporating a fully matched circuit in a miniature package, achieved through optimization of circuit design; and a PLL (Phase-Locked Loop) frequency synthesizer IC that has achieved low power consumption through a Bi-CMOS process suitable for high frequency analog LSIs.

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**Table 1 High frequency analog LSI product series**

We have been developing, and putting into commercial production, a PLL frequency synthesizer for use in cellular telephones and compound function high frequency LSIs with the PLL frequency synthesizer as the core.

Product Type Name	Function	Application
HD155001BT	1GHz PLL	Analog cellular
HD155002T	1GHz PLL/130 MHz, PLL + IF-VCO + transmit mixer	Analog cellular
HD155004T	130 MHz, all CMOS PLLs	Analog cellular
HD155007T	1GHz PLL/130 MHz	For PHS
HD155008T	1GHz PLL/130 MHz	For GSM

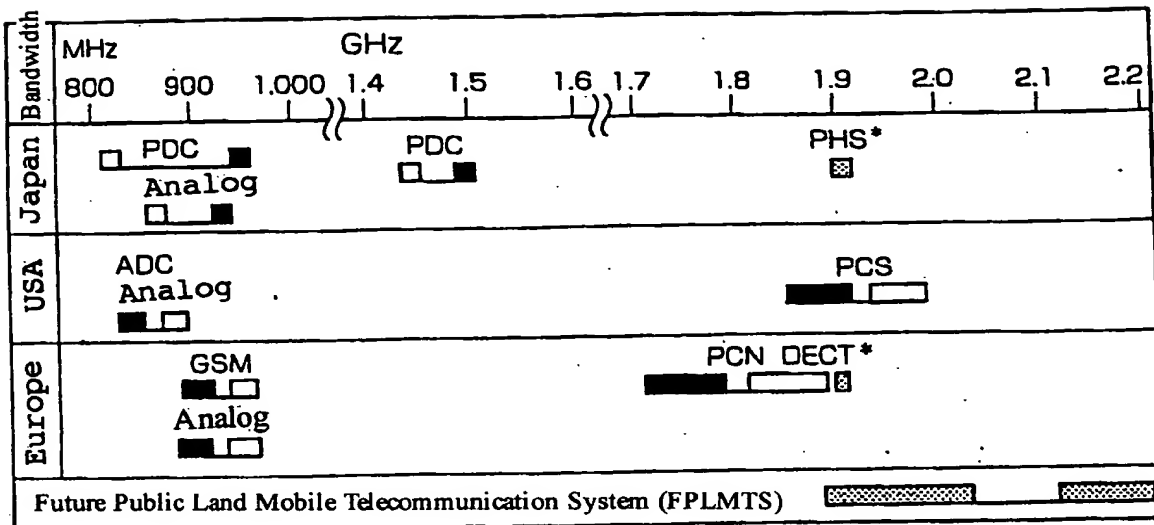
Note: Explanation for abbreviation  
IF-VCO (Intermediate Frequency-Voltage Controlled Oscillator)

**Table 2 Principal characteristics of the HD155007T**

The HD155007T dual PLL frequency synthesizer has been developed for use in the 1.8 to 2.0 GHz bandwidth in a digital system. It operates at low voltage (from 2.7V) and has low current consumption.

Item		Characteristics
Maximum prescaler input frequency		2 GHz min. (RF PLL), 510 MHz min. (IF PLL)
Maximum reference signal input frequency		20 MHz min.
Prescaler input sensitivity		-30 dBm typ.
Current consumption	In operation	12 mA typ.
	In power-saving state	400 nA typ.

Note: Explanation for abbreviations  
min. (minimum), typ. (typical)



**Abbreviation:**

PDC(Personal Digital Cellular)

ADC(American Digital Cellular)

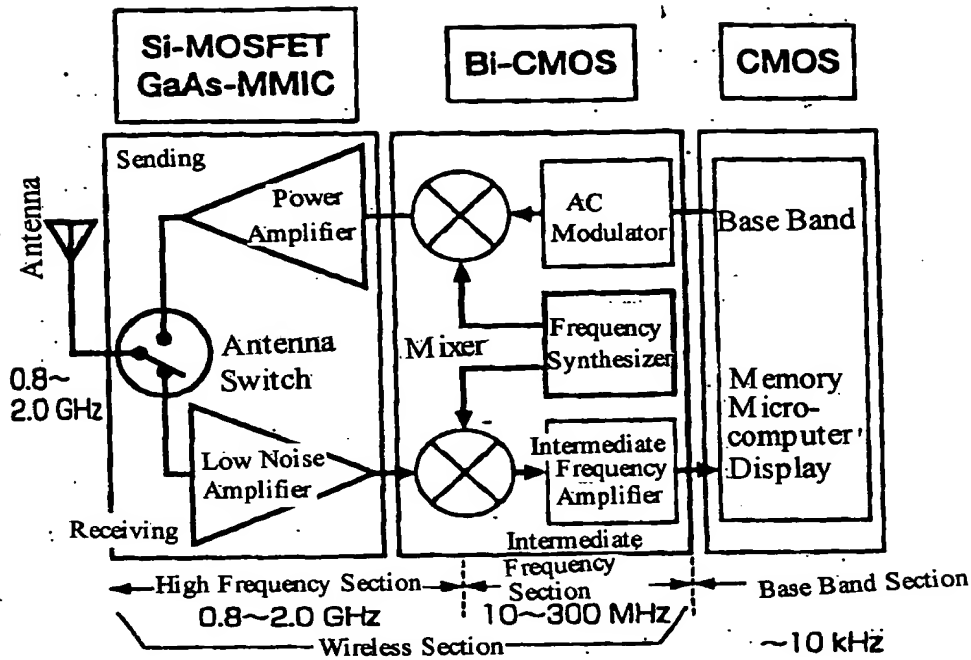
GSM(Global System for Mobile Telecommunications)

■ Send by cellular phones    □ Receive by cellular phones

\*Common for DECT and PHS: not determined for FPLMTS.

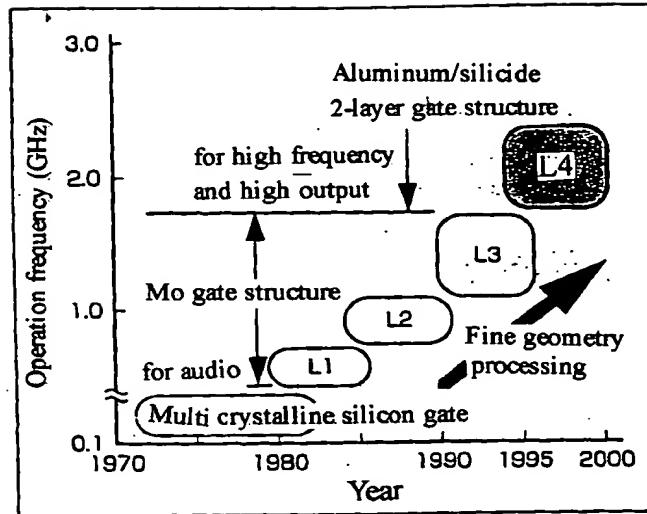
**Fig. 1 Frequency bandwidths used in mobile communication systems..**

Present mobile communication systems mainly use the 800 to 900MHz bandwidth, but to cope with the increasing number of subscribers new digital systems that use the high frequency 1.8 to 2.0 GHz bandwidth are being actively introduced. FPLMTS frequencies are being assigned for use in the worldwide mobile communication systems of the future.



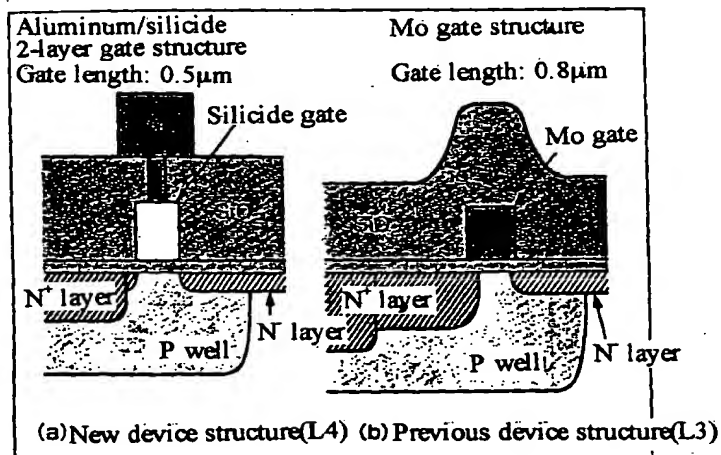
**Fig. 2 Basic block diagram and device technology of a cellular telephone.**

A cellular telephone consists of a wireless section which in turn consists of a high frequency section and an intermediate frequency section, and a base band section that performs control, input and output. An Si-MOSFET and GaAs-MMIC having superior frequency response are used in the high frequency section; in the intermediate frequency section, which requires both good high frequency performance and a high degree of integration, Bi-CMOS technology is used.



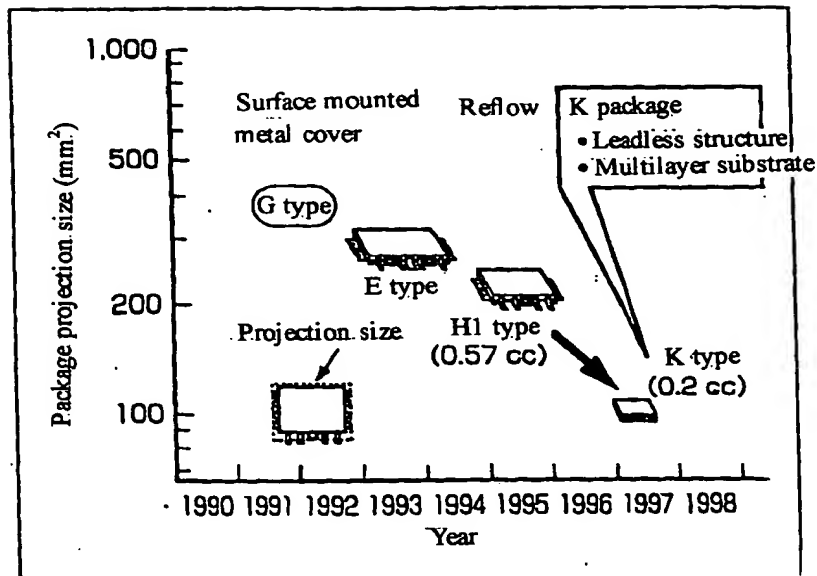
**Fig. 3 The high frequency Si-MOSFET development schedule at Hitachi Ltd.**

The Si-MOSFET was first developed for audio use, but Mo gate structure and fine geometry processing technology resulted in greatly improved high frequency response, and success was achieved as 800-MHz bandwidth in putting it into commercial production. This time we have developed an aluminum/silicide 2-layer gate structure, leading to a high frequency MOSFET (L4) that can be used in the 2 GHz bandwidth.



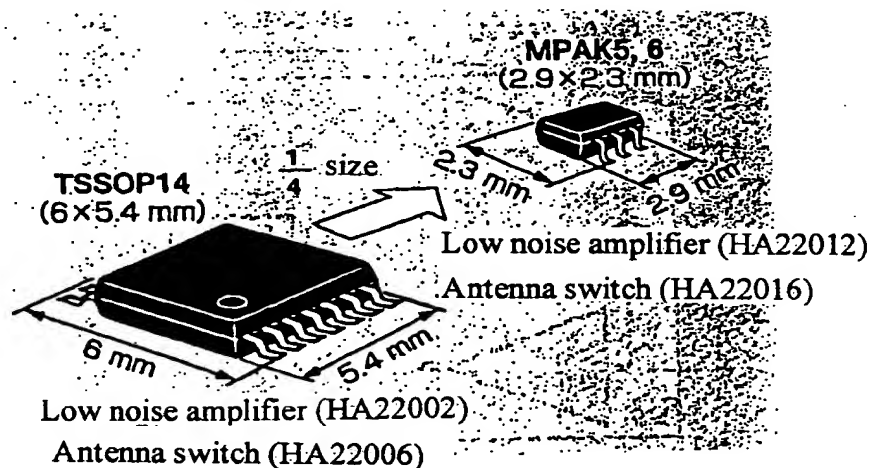
**Fig. 4 Cross-sectional structure of a MOSFET device.**

To achieve improved performance by reducing the gate length geometry, an aluminum/silicide 2-layer gate structure was developed to replace the previous molybdenum gate (the 0.8  $\mu\text{m}$  L3), resulting in the gate length of 0.5  $\mu\text{m}$ .



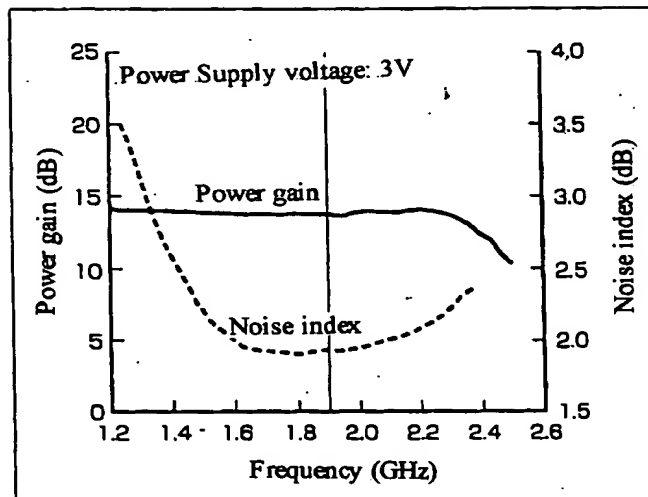
**Fig. 5 The development schedule for packages used in high frequency modules at Hitachi Ltd.**

To meet the demand for smaller high frequency modules, the new Model K package (0.2cc, about 1/3 the volume of previous models) with a leadless structure was developed using a multilayer ceramic substrate.



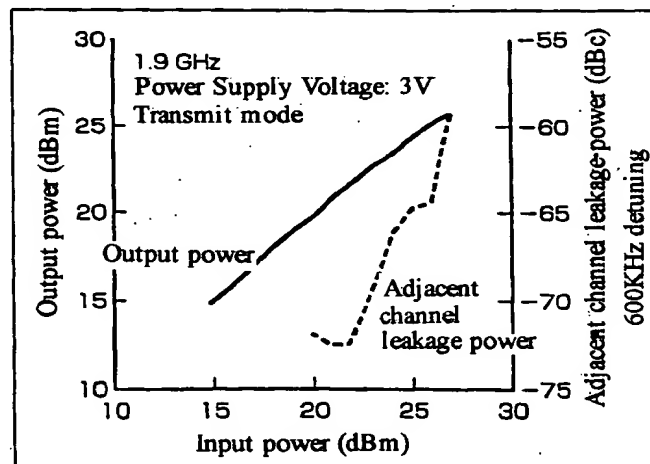
**Fig. 6 The GaAs-MMIC miniature package.**

By decreasing the size of the passive element on a GaAs chip and optimizing circuit design, chip size has been decreased, resulting in new miniature packaging (MPAK5, 6) about 1/4 the size of previous packaging.



**Fig. 7 High frequency response of the MMIC low noise amplifier (HA22012, outline MPAK5).**

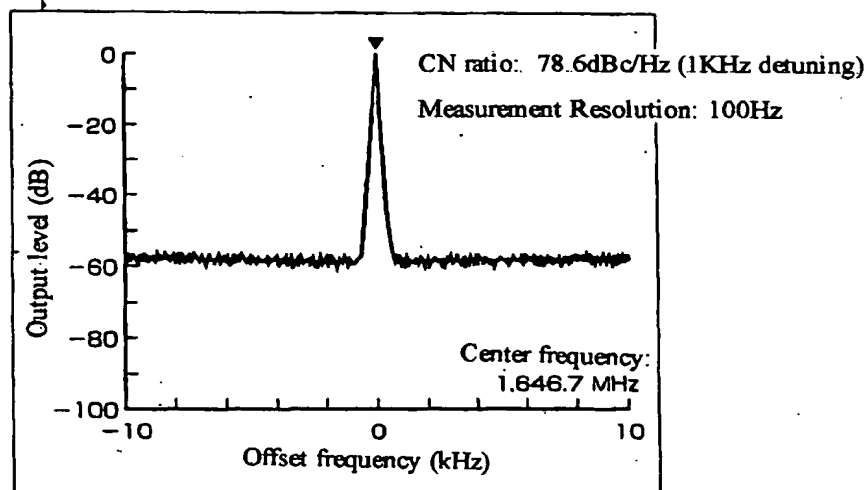
This device shows good frequency response, with power gain of 13.5dB, noise index of 1.9dB and output 3rd order intercept point 12.5dBm at frequency 1.9 GHz, power supply voltage 3V and operating current 3mA.



**Fig. 8 High frequency response of MMIC antenna switch (HA22016, outline MPAK6).**

At frequency 1.9 GHz and control voltage 3V, the insertion loss in transmit mode is 0.7dB. at the time of 1dB gain compression, with output of 27dBm or input of 26dBm (x/4 shift QPSK (Quadrature-Shift Keying) modulation signal) the 600KHz isolation adjacent channel leakage power is -65dBc and the isolation is 25dB. The high frequency response is shown here.





**Fig. 9 Output spectrum of the HD155007T.**

Excellent characteristics have been obtained: at a center frequency of 1,646.7 MHz and phase comparison frequency of 300 KHz, the phase noise is -78.6 dBc/KHz (1KHz detuning) and the spurious level is -77dBc (600KHz detuning ).